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Evaluating Groundwater Velocity in A Low-Permeability Fractured Shale

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Introduction

Numerous landfills and industrial activities in North America are situated such that chemicals emanating from these facilities are contaminating groundwater in underlying bedrock. In particular, this is the case for sites in southern Ontario and the Niagara Peninsula where the underlying materials consist of a thin veneer of overburden overtop moderately to highly fractured shale of the Ordovician Queenston Formation or the Cambrian Georgian Bay Formation. Because contaminant migration along fracture planes within the shale can be very rapid relative to unconsolidated media, accurate prediction of the direction, velocity and dilution of the contamination is especially important with regard to public health and safety.

Groundwater velocity predictions are usually based on direct hydraulic measurements of the permeability of fractures which is expressed as an equivalent single fracture aperture, 2b. Average groundwater velocity, $\bar{v}$, is then estimated from the expression:

$$\bar{v} = \frac{\rho g (2b)^2}{12\mu} \cdot \frac{dh}{dl} \qquad (1)$$

where ρ, g and μ are the density, gravitational acceleration and dynamic viscosity of the water, respectively. The hydraulic gradient, dh/dl, is usually determined from water level measurements in piezo-

meters or more correctly from multi-level casing strings which isolate individual fractures and fracture zones.

Equation (1) is derived from a conceptual model known as the cubic law in which water flow is between two smooth parallel plates separated by the width, 2b. Inspection of natural fractures in outcrop and core sample show that fracture surfaces are distinctly non-uniform and are characterized by a variety of aperture widths, regions where asperities contact and channels of reduced or enhanced opening. Consequently, the relationship between the 2b obtained from the results of hydraulic tests interpreted using the cubic law and the average mechanical or true aperature is unclear. This is evidenced by comparing the groundwater velocity predicted from apertures obtained from hydraulic measurement to that obtained from tracer experiments which show that hydraulically measured apertures (hereafter called hydraulic apertures) overestimate groundwater velocity in most cases (Novakowski et al., 1985; Raven et al., 1988).

The objective of this study is to investigate the relation between fracture apertures determined from hydraulic methods versus those determined using tracer experiments with the intent to resolve the role of the rough and heterogeneous character of natural fractures. This goal is addressed with a field study focussing on a single-flat lying fracture intersected by four boreholes of a seven borehole grid at a depth of about 10 m. Most common transient and steady-state single-well and multiple-well hydraulic tests were employed to determine the hydraulic aperture. The tracer apertures were determined from seven tracer experiments conducted using both injection-withdrawal and radial-convergent flow fields configurations.

Field Method

During the period of 1985 and 1986, a field site was chosen at which preliminary hydraulic tests revealed the presence of two largely unconnected flat-lying fractures at depths of 9.7 and 10.4 m below ground surface. The study site is located in Clarkson, Ontario on unused Petro-Canada property about 1.5 km north of the Lake Ontario shoreline. The fractures are in the Meaford-Dundas shale which

sub-crops in the Oakville-Mississauga area of southern Ontario and strikes North-Northwest.

The initial location of the fracture set and the subsequent characterization of the apertures and boundaries were carried out over 1986 and 1987. During 1986, a preliminary drilling program was conducted in which five 76 mm boreholes were drilled 15 m apart in two perpendicular rows of three (Figure 1). Examination of the core and preliminary constant-head test results showed four main fracture zones with the shallowest set at 9.5 m to 10.5 m exhibiting the highest permeability. Subsequent field work during 1987 focused on this set and two new boreholes, UW6 and UW7 were drilled during mid-summer solely to investigate this zone. After completion of the drilling, the precise location of each of the two fractures in all seven boreholes was determined using constant-head tests with a 0.1 m interval spacing.

On the basis of the constant-head test results, the upper fracture has a mean aperture width of about 120 µm (this is equal to an hydraulic conductivity of 1×10^{-6} m/s) and the lower fracture has a mean aperture of about 200 µm (hydraulic conductivity of 5×10^{-6} m/s). Figure 1 shows the approximate extent of each fracture within the study site. The boundaries indicated on Figure 1 are arbitrary and are drawn only to show interconnection between boreholes. For example, fracture no. 1, the upper fracture, hydraulically connects UW3, UW6 and UW7 but is not well connected to UW1, UW2, UW4 and UW5. On the basis of the larger aperture identified for the lower fracture, it was selected for the purpose of this study and all further hydraulic and tracer tests described in the following text were conducted in this fracture. Preliminary estimates of hydraulic head in the lower fracture indicate groundwater flow oriented towards the northeast with a gradient of 0.01.

In addition to constant-head tests, slug tests and steady-state and transient pumping tests were also conducted. The slug tests were carried out using a straddle-packer arrangement attached to a 1.5" I.D. standpipe in which the instantaneously induced rise or fall of water level was monitored using a pressure transducer. Slug tests were conducted in all boreholes except UW6. The pumping tests were

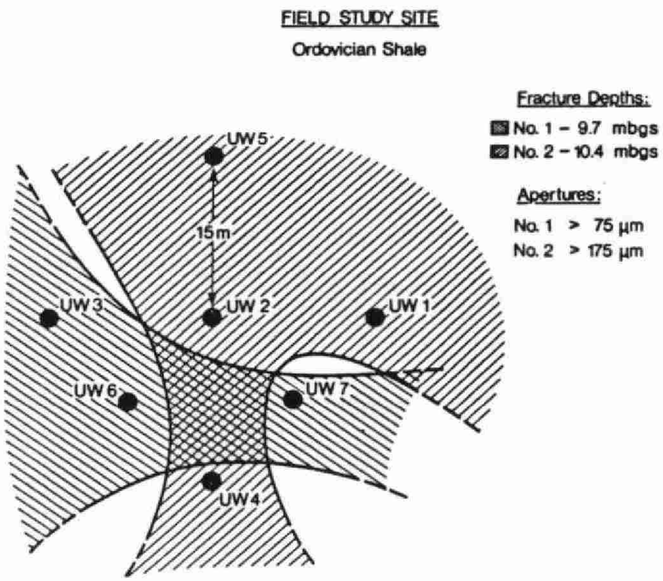

Figure 1. Approximate boundaries of the two fractures intersected by boreholes at the study site. Fracture no. 1 interconnects boreholes UW3, UW6 and UW7. Fracture no. 2 interconnects UW1, UW2, UW4, and UW5.

conducted also using a straddle packer arrangement except in this case the test fracture was completely isolated. Abstraction of water was carried out by pumping from surface through ¼" nylon tubing. Drawdown in the observation intervals also isolated by packers was monitored using pressure transducers. Pumping tests were conducted in UW5 and UW2 with observation in UW1, UW2 and UW4.

Two methods for induced-gradient tracer experiments were employed to compare to the results of the hydraulic tests; the injection-withdrawal method and the radial-convergent method. The injection-withdrawal tracer experiments were conducted by injecting water into one borehole and withdrawing water from another at the same flowrate. Sodium bromide tracer was introduced as a slug into the injection borehole once the flow field had achieved steady-state conditions. Tracer arrival at the withdrawal borehole was continuously monitored using a flow-cell arrangement and tracer concentration was measured in discrete samples of the withdrawn water. The fracture was isolated in both the injection and withdrawal boreholes using straddle packer arrangements. Injection and withdrawal flowrates and interwell hydraulic gradients were monitored on a continuing basis through the duration of each experiment. The radial-convergent tracer experiments were conducted in a similar manner except that continuous injection of water was not employed. A steady radial flow field was established around a borehole by pumping and tracer was introduced into the flow field from an observation borehole by pulse injection. Both tracer methods were employed for tests conducted between UW1 and UW2 and UW4 and UW2, with UW2 as the withdrawal borehole in all cases. The injection-withdrawal method only was employed for experiments conducted between UW2 and UW5, UW5 and UW4 and UW7 and UW3. Novakowski (1988) provides a more detailed description of the field methods employed for this study.

Results and Discussion

The constant-head hydraulic tests were analysed using the Thiem equation where the steady flow rate, Q, divided by the rise in hydraulic head, ΔH, is proportional to transmissivity, T:

$$\frac{Q}{\Delta H} = \frac{2\,\pi T}{\ln\,(r_e/r_w)} \qquad (2)$$

where r_e is the radius of influence (estimated at approximately 10 m for these tests) and r_w is the radius of the well. Fracture aperture is then calculated from the transmissivity using:

$$2b = \left(\frac{12\mu}{\rho g}\,T\right)^{1/3} \qquad (3)$$

Both the slug tests and transient pumping tests were analysed using type curve methods to obtain transmissivity. The steady-state pumping tests were analysed using equation (2) where the radial distance between the pumping and observation boreholes is substituted for r_e and ΔH is the difference in hydraulic head between the two wells.

The tracers experiments were analysed for fracture aperture by using analytical approximations to describe the streamline(s) between the injection and pumping borehole and solving the advection-dispersion equation along each streamline. The analytical approximations for the streamlines are based on the average travel time for the tracer and the interwell difference in hydraulic head. The aperture is determined by a trial and error procedure, varying the 2b to determine the location of the model peak.

Table 1 shows the results of the hydraulic tests and tracer experiments expressed as fracture aperture in micrometers along with the borehole interval isolated for each test. In general, distinction between the results of transient and steady-state hydraulic tests is immediately clear. The results of the transient hydraulic tests show consistently larger fracture apertures than those of the steady-state tests. This is a function of the radius of test influence and knowing that steady-state test results more likely reflect the properties of the fracture nearest the source borehole, the apertures determined from the transient tests probably reflect regions of the study fracture that have a slightly larger aperture and that are beyond the lateral extent of the study site.

On the basis of the relative uniformity of the apertures determined from the transient hydraulic tests conducted in borehole UW2 (the central borehole of the study site) there is no evidence to suggest non-radial flow effects which might indicate the presence of channeled flow. This suggests that the points of closure currently identified by boreholes UW3, UW6 and UW7 are relatively small in area and the boundaries to the fracture plane as drawn in Figure 1 are probably inappropriate.

Comparing the fracture apertures determined from the hydraulic tests to those from the tracer experiments, it is evident that the tracer apertures are consistently smaller by up to 50%. This observation is in agreement with the results of other field experiments reviewed in Raven et al. (1988). These results are significant with respect to predicting groundwater velocity in fractures because velocity is proportional to the square of the fracture aperture. Therefore, an aperture difference of a factor of 2, for example, translates into a four-fold difference in velocity.

An explanation as to why tracer apertures are always smaller than hydraulic apertures can be found based on the solute transit path length. Because we have established that natural fractures are rough and undulating, and we know that the fracture walls are in some degree of contact as evidenced by closure in UW3, UW6 and UW7, then the path travelled by the tracer in transit from the injection borehole to the pumping borehole may be very tortuous as the flow negotiates around the points of closure and areas of reduced opening.

To investigate this explanation, the tracer experiments between UW1 and UW2 and UW4 and UW2 were simulated by fixing the 2b to the size of the steady-state hydraulic aperture and modeling for the path length. Table 2 shows the modeled path lengths and values of tortuosity which are calculated by dividing the modeled path length into the actual interwell distance.

Table 1. Aperture widths (in μm) as determined from slug test, constant head test, tracer test and pumping test results.

Borehole	Aperture (μm)	Interval (mbgs)	
<u>Slug Tests</u>			
UW1	210	10.10 - 10.92	
UW2	267	10.16 - 10.98	
UW3	147	9.40 - 10.22	
UW4	226	10.21 - 11.03	
UW5	180	10.20 - 11.02	
UW6	-		
UW7	140	9.90 - 10.52	
<u>Constant Head Tests</u>			
UW1	229	9.90 - 10.72	
UW2	236	9.96 - 10.78	
UW3	135	9.10 - 9.92	
UW4	186	10.21 - 11.03	
UW5	164	9.80 - 10.62	
UW6	80	9.60 - 10.42	
UW7	120	9.30 - 10.12	
<u>Tracer Tests</u>			
UW1→UW2(I)	160	10.10 - 10.92	10.00 - 10.49
UW1→UW2(P)	132	10.10 - 10.92	10.00 - 10.49
UW2→UW5(I)	192	10.00 - 10.49	10.00 - 10.90
UW4→UW2(I)	155	10.20 - 11.02	10.00 - 11.49
UW4→UW2(P)	151	10.20 - 11.02	10.00 - 10.49
UW5→UW4(I)	164	10.40 - 10.89	10.20 - 11.02
UW7→UW3(I)	151	9.50 - 9.99	9.40 - 10.22
<u>Pumping Tests</u>			
UW5→UW2(T)	184	9.80 - 11.02	10.10 - 10.95
UW5→UW1(T)	179	9.80 - 11.02	10.10 - 10.95
UW2→UW4(S)	211	10.00 - 10.49	10.10 - 10.92
UW2→UW1(S)	215	10.00 - 10.49	10.20 - 11.02
UW2→UW1(T)	254	10.00 - 10.49	10.10 - 10.92
UW2→UW4(T)	228	10.00 - 10.49	10.10 - 10.92

T - transient
S - steady state
I - injection-withdrawal flow field
P - radial-convergent flow field

Table 2. Modeled path lengths and tortuosity determined from the tracer experiments.

	Path Length (m)	Tortuousity
UW1 to UW2(I)	19.0	0.79
UW1 to UW2(P)	23.0	0.65
UW4 to UW2(I)	20.6	0.73
UW4 to UW2(P)	20.6	0.73

The range of tortuosity is from 0.65 to 0.79 which is quite wide although not unrealistic in terms of the average angularity of flow (the vectoral direction of flow not directly towards the withdrawal well). Tortuosity of 0.65 gives an angularity of flow of 50° while 0.79 gives about 38°. The angle of flow in porous media is about 45°. Considering the complex possibility of pathways dependent on the aperture distribution, these values of tortuosity are probably reasonable.

On the basis of the results presented here and on other recent field evidence (Raven <u>et al</u>., 1988), it is apparent that using the cubic law to interpret the results of hydraulic tests will lead to erroneous predictions of groundwater velocity. Therefore a new conceptual model is urgently required with which the results of hydraulic tests can be utilized to predict velocity without relying on comparison to more costly and time consuming tracer experiments. On the basis of the preliminary modeling conducted for this study, it is likely that such a conceptual model will depend on the role of tortuousity during solute transport in natural fractures.

Summary

Comparisons of fracture aperture widths determined from the results of hydraulic tests and tracer experiments were made. Constant-head, slug, steady-state and transient pumping tests were employed to determine the fracture aperture, hydraulically. The tracer experiments were carried out in radial-convergent and

injection-withdrawal flow field formats. The tests were conducted in a discrete flat-lying fracture in Ordovician aged shale at a depth of approximately 10 m.

The results show that apertures determined from tracer experiments are consistently smaller than those obtained from hydraulic tests. The reason for this discrepancy is probably due to the influence of tortuous flow around reduced apertures and points of closure in the fracture plane. The development of a new conceptual model which can more accurately relate the results of hydraulic tests to a prediction of groundwater velocity, is required to reconcile these differences.

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